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Ground source heat pump combined with thermo-active building system with incorporated PCM for low-energy residential house

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1. Introduction

Since the mid 90's low energy buildings with significantly reduced energy consumption have been realised. This has been made possible by better insulated and more airtight building envelopes, balanced ventilation systems with heat recovery and utilization of passive solar heating. On the contrary, due to the increased levels of insulation, air tightness, and demands for comfort, the need for energy efficient cooling has arisen. Therefore it is essential to develop heating/cooling concepts that are passive and/or using very little primary energy.

Due to their high energy efficiency, ground source heat pumps (GSHP) have been under extensive research as a heating/cooling source within the concepts for low and net-zero energy residential houses (Hamada et al. 2000, Sakellari et al. 2004, IEA HPP-AN32-1 2011, Stene 2008, Liu 2008). An increase of the performance factor of these systems, compared to other types of heat pumps, is obtained by using the ground as a heat source with more moderate and balanced temperatures compared to ambient.

Heat to/from a conventional GSHP is extracted/rejected from/to the ground via a ground heat exchanger (GHE). The design of the GHE will affect heat pump system performance, auxiliary pumping energy requirements, and installation costs.

Ground-source heat pump systems for residential houses are often designed to cover around 80% of the total annual heating and cooling demand. Due to that reason these systems are frequently unable to provide the necessary heating or cooling power at peak demand and there is a time mismatch between energy supply and demand. A suitable thermal storage is therefore needed to overcome this time lag.

Thermally activated building systems (TABS) use the large thermal capacities of the building structure as thermal energy storage and are thereby integrated in the overall energy strategy of the building (Meierhans 1993, Olesen 2000, Olesen et al. 2006). Heating/cooling gains during the day are stored in solid floors and slabs, which are then recooled/reheated at an appropriate time by means of a water pipe system – the extracted energy being rejected to the ground using the GSHP system. Through the intermediate storage of energy in the building mass, peaks in energy demand are flattened. In addition, there is no need to instantly supply the heating and cooling demand of the space to the slabs. Heat and cold can be transferred with time shift and at power levels which may differ from the actual demand.

While, in buildings with heavy construction, the concrete slabs provide the necessary thermal mass for the TABS system, there should be found alternative solutions for lightweight buildings. Latent storage in phase-change materials (PCMs) has turned out as being the main focus in ongoing engineering research. PCM-panels with hydronic pipes could be the alternative TABS system for lightweight buildings, where the PCM gives the necessary thermal mass, while the hydronic pipes provide active charging and discharging of the PCM (Koschenz & Lehmann 2004, Kalz et al. 2007).

The aim of the present work is to evaluate and optimize the performance, in relation to thermal comfort and energy consumption, of a GSHP system coupled to thermally activated ceiling panels with incorporated PCM. The concept, being part of the energy supply system of a 75 m^2 low-energy lightweight residential house, will be analyzed through computer simulations using TRNSYS 17 (Klein et al. 2009), for two different climatic locations in Europe, Copenhagen (DK) and Madrid (ES).

2. Case study description

A reference model was developed in order to study the proposed concept of GSHP system combined with TABS-PCM system. The analyses concentrate on the energy performance and thermal comfort achieved by using different ceiling embedded pipes system configurations.

Building envelope

A 75 m^2 one storey single-family lightweight (wooden panels and insulation) residential house has been chosen for this study. The building envelope is well insulated and windows are of triple glazed low energy type. The house is built as a single space except for the bathroom. The total conditioned volume is 220 m^3. In Figure 1 is shown a 3D model and a floor-plan layout of the house. General building information is summarized in Table 1.

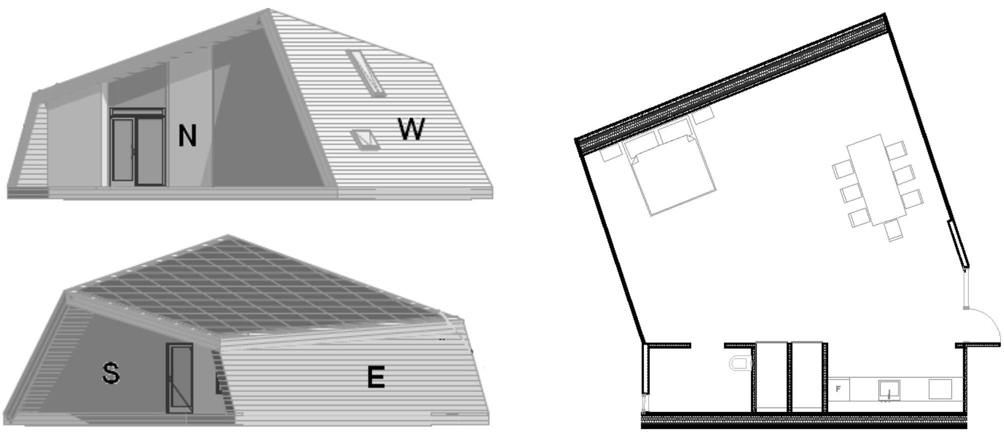

Figure 1. House 3D model and floor-plan layout

The house has a mechanical ventilation system with heat recovery supplying 172 m^3/h. The ventilation system is not intended to be used for heating and cooling purposes but rather to remove sensory pollution and provide the required level of relative humidity in order to achieve a pleasant indoor climate. The supply air temperature is controlled to a minimum of 17°C during the heating season and a maximum of 22°C during the cooling season.

In order to reduce peak cooling loads during summertime, the windows are provided with external shading that is controlled by the zone temperature. When the zone operative temperature exceeds 24°C, external shading (0.7 shading coefficient) is applied on the windows.

Floor heating and ceiling cooling system

The heating need of the house is addressed by embedded pipes in the floor and the cooling needs are addressed by embedded pipes in the ceiling and by the pipes in the floor, if necessary.

The floor system is a sandwich structure of chipboard, heat conductive plate, PEX piping of 13 mm internal diameter at a spacing of 20 cm, and parquet layer (Figure 2). The embedded system is divided in 5 parallel circuits. The system is designed to supply a total water mass flowrate of 250 kg/h. The heating capacity of the floor system is 32 W/m2 (operational floor area is 75 m2).

Table 1. General information for the building.

External Walls	South	North	East	West	Floor	Roof
Area, m^2	19	36	18.1	43.7	75	61
U-value, W/m^2K	0.09	0.09	0.09	0.09	0.09	0.09
Windows	South	North	East	West	Floor	Roof
Area, m^2	14.15	25.6	-	2.24	-	-
U-value, W/m^2K	0.7	0.7	-	0.7	-	-
Solar transmission	0.4	0.4	-	0.4	-	-
Time of the day	6-8; 21-22	17; 19-20	9-16	18	23-1; 3-5	2
Internal loads, W/m^2	6.28	6.51	0.23	8.9	3-32	4.54

The ceiling system is a sandwich structure of polyester board, heat conductive plate, PEX piping of 8.6 mm internal diameter at a spacing of 12.5 cm, and plywood layer for internal finishing. The embedded system is divided in 5 parallel circuits. The system is designed to supply a total water mass flowrate of 250 kg/h. The cooling capacity for the system is 35 W/m^2 (operational ceiling area is 61 m^2).

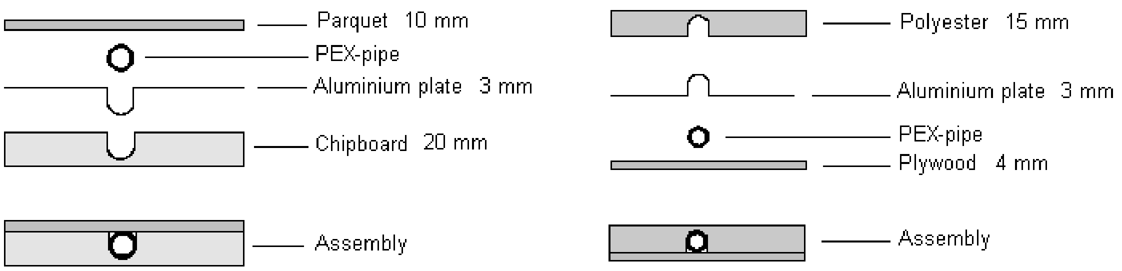

Figure 2. Embedded pipe system: floor structure (left) and ceiling structure (right)

The control of the floor/ceiling heating and cooling system is split up in a central control and a room control. The central control (Figure 3) will, according to the outside climate, regulate the supply water temperature to the floor/ceiling system. The room control (on/off) will then control the water flow rate according to the set-point room temperature. For the heating season operative room temperature set point of 21°C ±1K and for the cooling season operative room temperature set point of 25°C ±1K are selected, according to the recommendations for thermal environment Class II of EN 15251(2007).

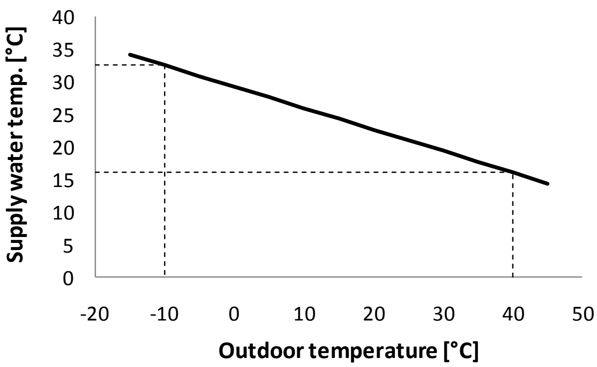

Figure 3. Heating/cooling curve for supply water temperature

PCM ceiling panels with embedded pipes

An important alternative to the ceiling cooling system with embedded pipes is the utilization of thermally activated ceiling panels (TABS) with Phase Change Material (Figure 4). PCM panels with embedded pipes can significantly increase the thermal inertia of the lightweight residential house. The high storage density of the PCM material, and the active utilization of the stored thermal energy by charging/discharging the panel by water driven TABS, will result in shifting the cooling demand from peak hours to off-peak hours, and will provide an efficient means of keeping the operative indoor temperature in the desired comfortable range.

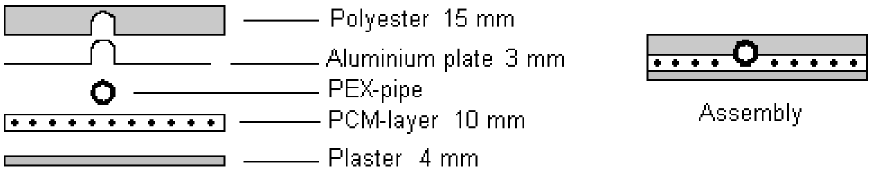

Figure 4. Ceiling panel with PCM

The PCM panels are built as a sandwich structure similar to the ceiling system - polyester board, heat conductive plate, PEX piping of 8.6 mm internal diameter at a spacing of 12.5 cm. The finishing layer of plywood is substituted with a layer of plaster in order to decrease the thermal resistance and increase the heat flux between the PCM and the room air. The hydronic system is designed to supply a total water mass flowrate of 340 kg/h when there is a need for discharging (solidifying the melted material) the PCM.

The PCM materials investigated in the computer simulation study are two salt hydrate materials with melting temperatures of 22°C and 24°C. The latent heat of the salt hydrate materials are the same, however they differ in the melting range and in the crystallization temperature. The specific data of the investigated PCM materials is summarized in Table 2.

Table 2. Thermal properties of the PCM materials

Material	Salt hydrate, SH24	Salt hydrate, SH22
Melting range, °C	22-26	20-24
Crystallization temp., °C	22	20
Spec. latent heat, kJ/kg	145	145

The control of the PCM ceiling system is activated during the cooling season and is similar to the embedded floor/ceiling system, split up in a central control and a room control. The central control (Figure 3) will, according to the outside climate, regulate the supply water temperature to the PCM panels system. The room control (on/off) will then control the water flow rate according to the set-point room temperature for cooling.

The control of the system gives priority to passive utilization of the PCM panels. Heat is absorbed during the day and discharged by the cool night temperatures. The active mode of operation begins when the daily room temperature (6-22 o'clock) exceeds 25°C. The control is set to 'on' during night time (23-5 o'clock), water is run through the embedded pipes, and the PCM material is allowed to discharge the heat absorbed during the day. When the absorbed heat is discharged the control is set to 'off'. During the day, the PCM panels work passively, absorbing heat from the house. In situations when the PCM panels have inadequate capacity to provide the required room temperatures (room operative temperatures exceed 26°C), the floor system is used to provide supplementary cooling during daytime.

The performance of the PCM panels is evaluated using a simulation tool integrated into the numerical simulation environment TRNSYS 17. The tool, developed by Dentel et al. (2010), allows simulating the room behaviour in buildings with PCM in active wall constructions (for e.g. chilled ceilings).

Ground Source Heat Pump System

Heat is extracted/rejected from/to the ground via a GSHP-borehole heat exchanger system. For a small residential house, of the size considered in the present work, it is normally enough to have one borehole. The depth of the borehole depends on the heating/cooling load, the ground thermal conductivity, the natural temperature in the ground, the ground water level, etc. The GHE used was constructed of a single U-pipe inserted in a borehole of a depth of 100 m. The main parameters of the GHE design are listed in Table 3.

Table 3. Ground heat exchanger parameters and soil properties

Pipe inside (outside) diameter, m	0.013 (0.016)
Pipe thermal conductivity, kJ/h.m.K	1.44
Fluid thermal conductivity, kJ/h.m.K	2.066
Fluid specific heat, kJ/kg.K	4.19
Fluid density, kg/m3	1000
Soil density, kg/m3	2400
Soil conductivity, kJ/h.m.K	6.3
Soil specific heat, kJ/kg.K	0.84

The heat pump is a water-to-water type with a nominal output capacity of 2 kW. Catalogue performance data in Figure 5 illustrate the range in efficiency with respect to inlet load and source water temperatures. The heat pump was controlled with an aquastat in order to deliver the required supply water temperature for the floor heating and cooling system with a deadband of ±1K. For the cooling season a passive cooling mode was given priority, in which the heat pump was bypassed and the supply water temperature was conditioned, through a heat exchanger, by the cool fluid circulating in the GHE. When the capacity of the GHE was not sufficient to provide the required water temperature, the heat pump started operation.

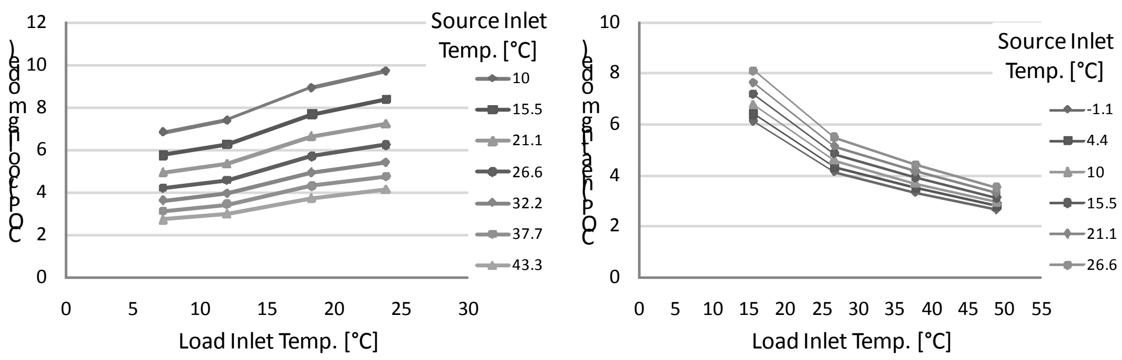

Figure 5. Heat Pump Efficiency – cooling (left) and heating (right) mode

Boundary conditions

The meteorological ambient boundary conditions correspond to the cool climate of Copenhagen (Denmark) and hot climate of Madrid (Spain). The external temperature data for winter and summer design days are -12°C and 30°C for Copenhagen, and -8°C and 40°C for Madrid. Summer period is from 1 May to 30 September, and winter period from 1 October to 30 April.

Floor and ceiling embedded pipe systems for heating and cooling – Case studies

In order to evaluate the performance in relation to energy consumption and indoor climate, three different embedded pipes system designs for heating and cooling the residential house were investigated, Table 4. For heating purposes the system with embedded pipes in the floor is used in all cases. For cooling purposes system with embedded pipes in the ceiling or systems with thermally activated ceiling panels with PCM with melting temperatures of 22°C or 24°C were used. The proposed system designs were replicated for the climatic locations of Copenhagen and Madrid.

Table 4. Heating and cooling systems – Case studies

Case	Location	System for Heating	System for Cooling
CPH 1	Copenhagen	floor embed. pipes	ceiling embed. pipes (+ floor embed. pipes)
CPH 22	Copenhagen	floor embed. Pipes	PCM 22 panel (+ floor embed. pipes)
CPH 24	Copenhagen	floor embed. Pipes	PCM 24 panel (+ floor embed. pipes)
MAD 1	Madrid	floor embed. Pipes	ceiling embed. pipes (+ floor embed. pipes)
MAD 22	Madrid	floor embed. Pipes	PCM 22 panel (+ floor embed. pipes)
MAD 24	Madrid	floor embed. pipes	PCM 24 panel (+ floor embed. pipes)

3. Results and discussion

Energy Consumption

In Figure 6 are presented the results for the annual energy consumption for the three system configurations. It can be seen that for the climatic location of Copenhagen, there is no significant difference between the performance of the three systems. The use of PCM panels gives slight advantage compared to the system with embedded pipes. The passive utilization of the PCM panels during winter time results in 3% (PCM with 24°C melting temperature) to 6% (PCM with 22°C melting temperature) decrease of the annual energy consumption for heating. Due to the low energy demand for cooling, there is no distinguishable advantage of the use of PCM panels compared to the embedded pipes system.

For the climatic location of Madrid, the advantage of adding thermal mass in the house, by using the PCM panels system, could be clearly distinguished. The passive utilization of the PCM panels during winter time results in 9% (PCM with 24°C melting temperature) to 12% (PCM with 22°C melting temperature) decrease of the annual energy consumption for heating. For the cooling season, the systems with PCM panels use about 50% less energy for providing the necessary cooling for the house.

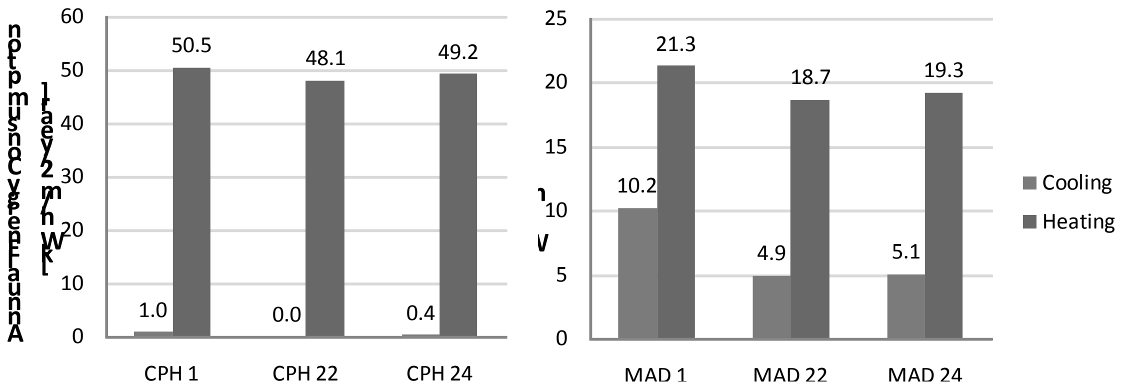

Figure 6. Annual energy consumption

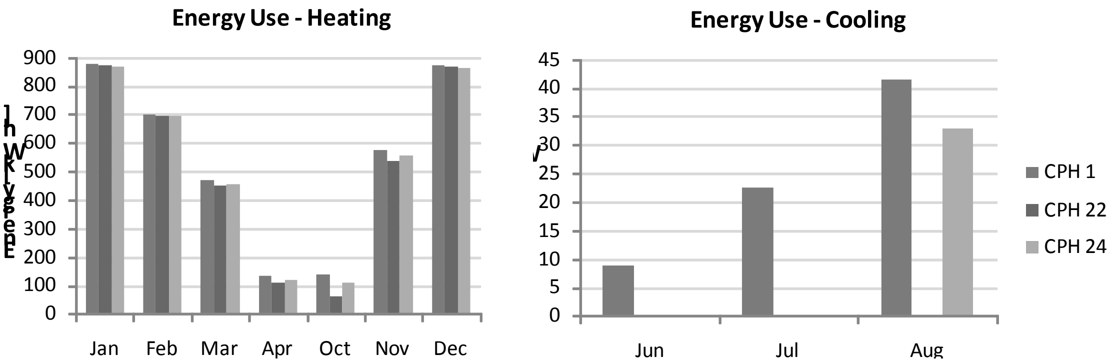

Figure 7. Energy consumption for heating and cooling on monthly bases, for Copenhagen

In order to further understand the benefits of using the different systems, the energy consumption for heating and cooling on monthly bases is shown in Figure 7 (for Copenhagen) and Figure 8 (for Madrid).

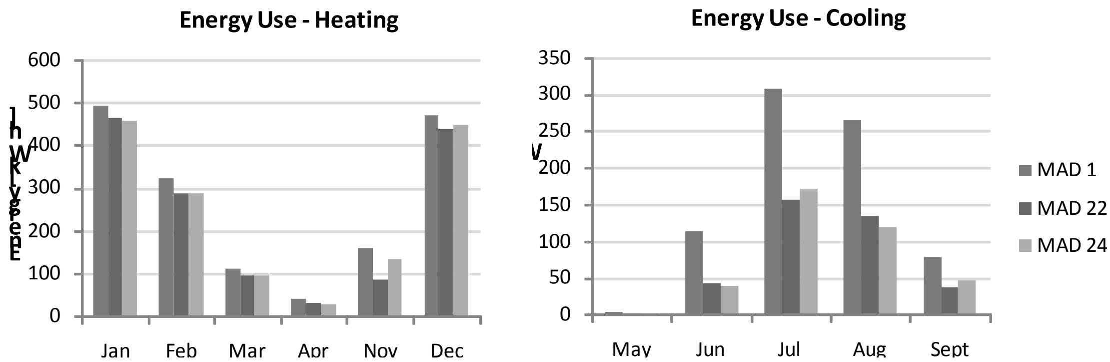

Figure 8. Energy consumption for heating and cooling on monthly bases, for Madrid

For the heating season it can be seen that the systems with PCM panels have advantage during the transition months of April, October and November, when there is a higher room temperature variation during day and night, which enhances the passive utilization of the PCM material. For the cooling season, the added thermal mass by using the PCM panels has almost completely removed the need for active cooling for the location of Copenhagen. For the climatic location of Madrid, significant energy need reductions for cooling are observed during the whole cooling season, when the systems with PCM are used.

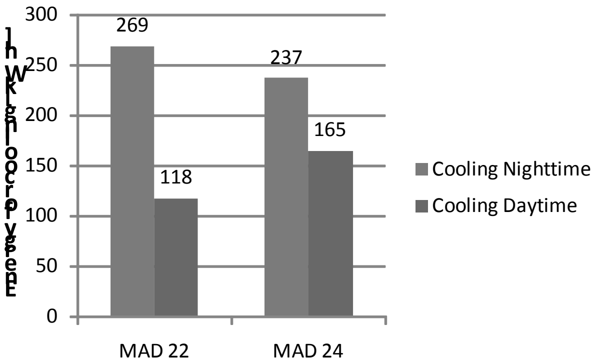

Figure 9. Energy supply for cooling during daytime and nighttime (peak load shifting), for Madrid

In Figure 9 is shown the cooling energy delivered during nighttime (PCM panels) and the supplementary cooling provided instantaneously by the embedded pipes in the floor during daytime, for the two systems with PCM panels for the location of Madrid. The increased thermal inertia of the lightweight residential house, by using the systems with PCM, has resulted in shifting large part of the cooling demand of the house from the peak hours during the day to off peak night hours. Compared to the system with ceiling embedded pipes, there has been no need to instantly supply all the cooling demand of the space. Cooling has been transferred with time shift and at power levels much lower than the actual demand.

GSHP system efficiency

In Figure 10 and Figure 11 are shown the results for the GSHP system efficiency in terms of system coefficient of performance (including ground source heat pump coefficient of performance and energy used by circulation pumps).

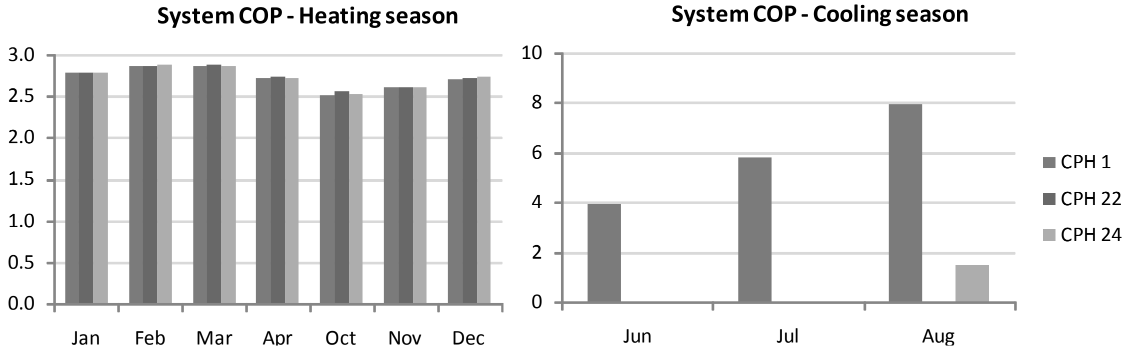

Figure 10. GSHP system efficiency, for Copenhagen

For the heating season, no any advantage or disadvantage by using any of the three system configurations can be seen. For the cooling season, the cooling energy needed is provided by free cooling, where the GSHP has not been used in any of the three studied cases. All the necessary energy for cooling is provided by using only the ground heat exchanger.

It can be seen that during the cooling season the system with embedded pipes has much higher system COP compared to the systems with PCM panels. However, that cannot be an indicator for being the better choice of system, since, as previously shown, the total energy consumed by the system with embedded pipes is twice as much as the systems with PCM panels. The lower system COP of the systems with PCM panels could actually be as a result of the low energy demand for cooling, where there is a high contribution of the electrical energy used by the circulation pumps to the total energy used for cooling.

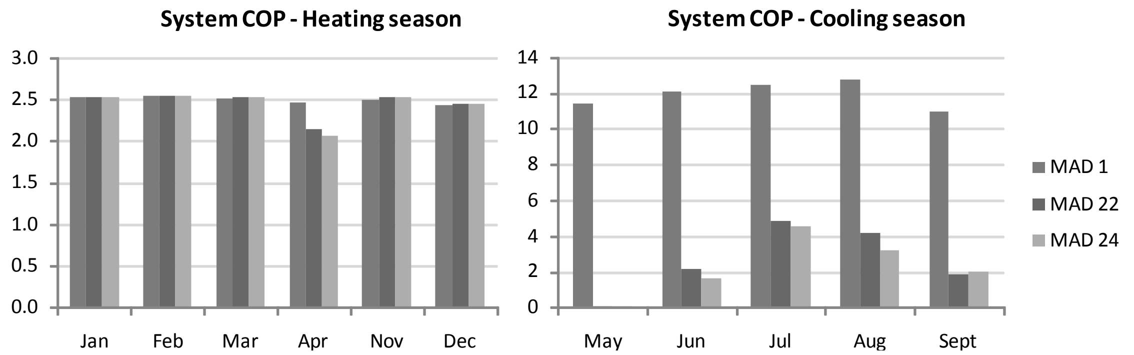

Figure 11. GSHP system efficiency, for Madrid

Indoor thermal environment and passive and active thermal mass utilization

Since one of the main criteria for system performance is related to the provided thermal environment, in Figure 12 and Figure 13 are shown the indoors operative temperature variations during representative weeks from the heating and cooling seasons for the two climatic locations considered. It can be seen that all system configurations considered have proved capable of providing the required thermal environment.

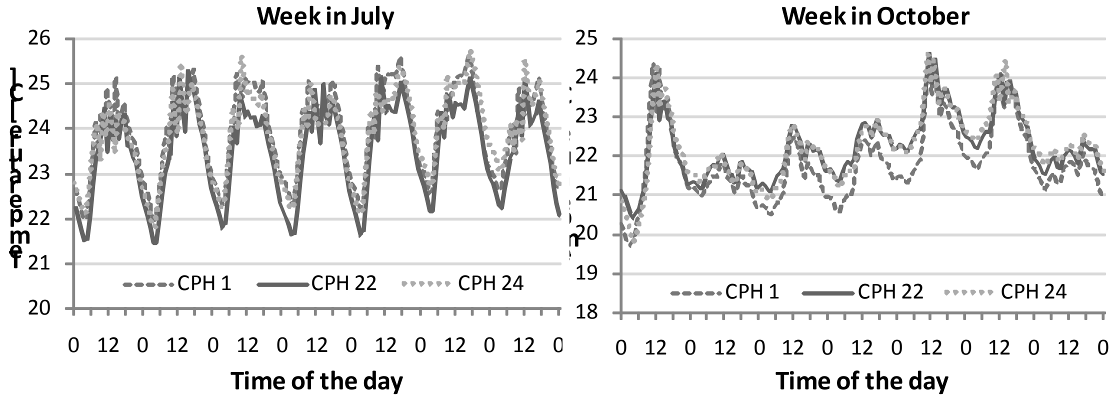

Figure 12. Indoors operative temperature variation, for Copenhagen

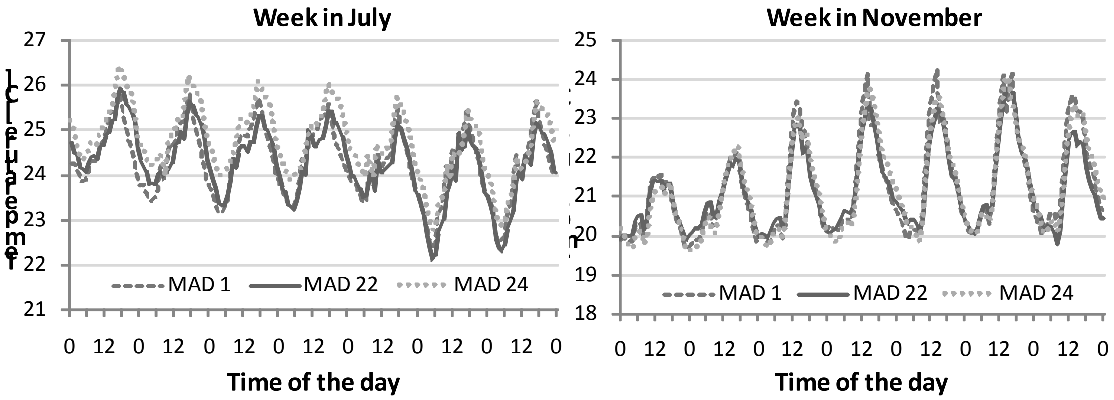

Figure 13. Indoors operative temperature variation, for Madrid

As previously discussed, the increased thermal mass of the house, by the use of PCM panels, has resulted in decrease of the annual energy consumption for heating and cooling. The active utilization of the PCM panels has resulted in significant load shifting from peak day hours to nighttime. However, the main driving force for the energy consumption reduction should be attributed to the passive utilization of the PCM during both the heating and the cooling season.

Table 5. Energy consumption during representative weeks from the heating and cooling seasons

Case	Energy consumption [kWh]			
	Heating – Week in Oct/Nov		Cooling – Week in July	
	Active	Passive	Active	Passive
MAD 1	103.9	0	39.2	0
MAD 22	80.5	23.4	15.8	23.3
MAD 24	96.8	7.1	21.6	17.6
CPH 1	8.6	0	6.6	0
CPH 22	0	8.6	0	6.6
CPH 24	4.3	4.3	0	6.6

In Table 5 is shown the energy demand of the house covered by passive and active means, for the two representative weeks from the heating and cooling seasons. It can be seen that for both periods significant part of the heating and cooling demand is covered by passive utilization of the PCM. That phenomenon can be correlated with the indoor temperatures, shown in Figure 12 and Figure 13, which daily variation is within the melting range of the PCMs used.

4. Conclusions

The combination of GSHP with low temperature heating and high temperature cooling integrated in the building structure is an energy efficient concept to provide thermal comfort in residential buildings. Combining the system with increased thermal mass of the building by using phase change material (PCM) helps decreasing the peak loads, transfer the need for heating and cooling to times of the day with less peaks on the energy grid, and decreasing the annual energy consumption for heating and cooling.

For both geographical locations the energy supplied for cooling has been obtained by passive means, without use of the heat pump, utilizing only the ground heat exchanger.

From the presented results about energy use and thermal environment, the systems with PCM panels have shown clear advantage compared to the system with embedded pipes. It should be pointed out the importance of PCM melting/solidifying temperatures, in order to integrate the TABS-PCM system in the overall energy strategy of the residential unit, and in providing the required thermal comfort in the house. The use of PCM with melting temperature of 22°C has shown a tendency to be the more favorable choice of material. However, there should be done further in-depth analyses and investigation of control strategies to better understand and utilize the full potential of the systems with PCM panels.

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